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Education in Process Systems Engineering: Why it matters more than ever and how it can be structured

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Dedication

To the memory of Professor Roger W.H. Sargent (14 October 1926 – 11 September 2018).
Professor Sargent is one of the great pioneers in Process Systems Engineering, having a sustained and powerful impact on the field, as well as leaving a global legacy of academic and industrial practitioners.

Abstract

This position paper is an outcome of discussions that took place at the third FIPSE Symposium in Rhodes, Greece, on June 20–22, 2016 (<http://fi-in-pse.org>). The FIPSE objective is to discuss open research challenges in topics in Process Systems Engineering (PSE). Here, we discuss the societal and industrial context in which systems thinking and process systems engineering provide indispensable skills and tools for generating innovative solutions to complex problems. We further highlight the present and future challenges that require systems approaches and tools to address not only ‘grand’ challenges but any complex socio-technical challenge. The current state of Process Systems Engineering (PSE) education in the area of chemical and biochemical engineering is considered. We discuss approaches and content at both the unit learning level and at the curriculum level that will enhance the graduates’ capabilities to meet the future challenges they will be facing. PSE principles are important in their own right, but importantly they provide significant opportunities to aid the integration of learning in the basic and engineering sciences across the

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whole curriculum. This fact is crucial in curriculum design and implementation, such that our graduates benefit to the maximum extent from their learning.

1. The necessity of systems thinking – challenges, concepts and practice

The ability to understand complex systems is at the heart of current and future challenges for improving life on the planet. By nature, these challenges are ones that require engineering of innovative solutions. Numerous existing and emerging challenges have been highlighted by organizations such as the US National Academy of Engineering¹, the UK Royal Academy of Engineering, the United Nations Development Programme² and professional engineering organizations such as the American Institute of Chemical Engineers (AIChE) and The Institution of Chemical Engineers (IChemE).

The so-called *Grand Challenges* for engineering require systems approaches due to their inherent complexity and their interdisciplinary nature but also because the challenges are most often encountered in the realm of the socio-techno-economic- nexus, and include:

- Purification and provision of water
- Energy
- Fighting hunger and poverty
- Sustainable technologies and circular economy
- The food-water-waste nexus
- Health care
- Carbon and the environment
- Cyber security
- Risk and safety

¹ <http://www.engineeringchallenges.org/challenges.aspx>

² <http://www.undp.org/content/undp/en/home/sustainable-development-goals.html>

Developing the knowledge, skills and dispositions that allow engineering graduates to effectively tackle such challenges must be a central part of a professional engineer's education. Systems thinking demands the ability to move effectively across the spectrum of reductionist and holistic approaches as fundamental concepts are applied in an integrated manner. The actions of synthesizing and analysing must be exercised to achieve desired outcomes. Process Systems Engineering requires competency in a range of tasks, techniques and tools that produce designs and solutions to problems arising in complex situations. Figure 1 sets out the landscape of key elements within a systems perspective to illustrate the PSE role in education and professional practice.

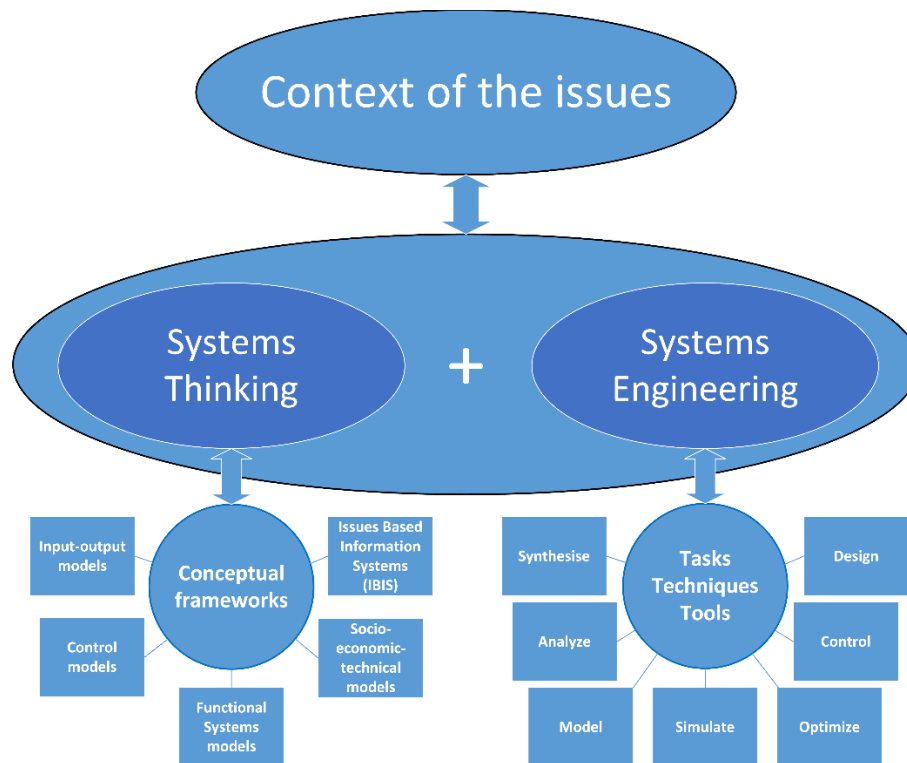


Figure 1: A simplified view of systems thinking and engineering

Major issues require systems thinking driven by a range of system conceptualizations (Arnold and Wade 2015). Some fundamental aspects are important in any system: its *boundaries*, the *parts* or *elements*, the *interconnections* amongst parts, the *functions* and *goals* of the system. Systems

thinking is the skill and mental activity that forms and arranges those ideas in our minds into suitable maps to reality (models), and allows us to develop a wide range of quantitative analyses and outcomes. These can include: prediction, improvement, control and resilience. Conceptualizations can range from simple to complex, capturing not just technical considerations but also social, economic and environmental aspects, often leading to multilevel, hierarchical perspectives of the problem (Mesarović, Macko et al. 1970).

Integrated with those conceptual frameworks are the tasks, techniques and tools that provide insights, solutions and the options for decision making. Tasks can include modeling in many forms, synthesis and analysis along with data acquisition, treatment and use. Amongst numerous tasks are design, control, diagnosis, and optimization, performed with an ever-growing set of techniques or methodologies, supported by many software and IT infrastructure tools.

How can we better address the curricular challenges in higher education to effectively prepare current and future graduates to successfully grapple with the complex challenges in their professional life? This position paper puts forward the view that within the cognate areas of chemical, biochemical, process engineering and the like, education for Process Systems Engineering skills must be a core part of any curriculum, tightly integrated with the other elements.

In what follows, we deal with systems thinking applied to the engineering and operation of complex processes. This perspective leads to the formation of PSE as an integrative discipline in chemical and process engineering. In exploring and analyzing the current educational importance of PSE, we consider key graduate outcomes across three principal areas:

- Knowing: the knowledge areas that should be addressed,
- Acting: the capabilities to take up knowledge and use it in new and challenging situations, and

- Being: the professional attitudes, dispositions and personal skills required

These three areas of *Knowing*, *Acting* and *Being*, form a design schema (Barnett and Coate 2005) that can guide thinking around educational designs

2. Process Systems Engineering – some history, scope and role

The 1950s application of systems engineering in the process industries, as seen in work at Monsanto, was a precursor to the subsequent development of PSE as a new focus within chemical engineering (Williams 1961). In commenting on the role of systems thinking and engineering in chemical engineering applications, Theodore J. Williams, a research and development engineer at Monsanto, wrote almost 60 years ago:

“... systems engineering has a significant contribution to make to the practice and development of chemical engineering. The crossing of barriers between chemical engineering and other engineering disciplines and the use of advanced mathematics to study fundamental process mechanisms cannot help but be fruitful. Study of transient and dynamic behavior will undoubtedly produce radically changed design methods and results. The use of computers and the development of mathematical process simulation techniques may result in completely new methods and approaches which will justify themselves by economic and technological improvements.”

At a similar time, pioneers from academe such as Roger Sargent voiced similar opportunities regarding the important integrative, synthesis role that systems engineering should provide (Sargent 1963, Sargent 1967). That perspective has proven to be highly successful, and continues to be so. Many of those issues were revisited and further emphasized by John Perkins (Perkins 2002) in 2002, in his review of PSE education history and trends.

Since the 1960s, this relatively new discipline has succeeded in realizing remarkable achievements. The tools and methodologies that have been developed by the PSE community for modeling, simulation, process synthesis, optimization, unit or plant-wide control and supply chain management are widely used for engineering and operation of processing plants.

The multitude and versatility of these techniques and tools support mathematical modeling and simulation from the molecular scale to flowsheets and global supply chains, the Design of Experiments (DoE), optimization of plant design and retrofitting, production planning, scheduling and operations and advanced control. Such approaches are routinely used by many industries: in petrochemicals, base and specialty chemicals, food and drink, pharmaceuticals, and many others. The ultimate goal is to design and operate processing plants such that the desired products are obtained in a safe, resource and energy efficient manner whilst being profitable, achieving high environmental standards which consistently satisfy the needs of customers and society.

The scope of PSE has broadened continuously, to systems design and operation in biotechnology, energy and water systems, semiconductor manufacturing, as well as the prediction of complex properties such as protein folding, solvent selection, and product design. PSE is core to the education of chemical and process engineers, as it addresses the design and operation of individual units and plants, production complexes, and supply chains in a holistic and systematic manner based upon rigorous theoretical foundations. PSE extrapolates naturally to “processes” in the widest sense, whether biological, techno-economic or social. PSE addresses the systematic building of models on different levels of detail and aggregation and of different mathematical forms, for their use in simulation, design optimization, control, planning and scheduling.

In 2014, Professor Sir William Wakeham (a physicist by training), formerly of Imperial College London and President of the UK Institution of Chemical Engineers raised the question: “Process Systems Engineering: an enhanced role in the curriculum?”³. He called for a change in chemical engineering curriculum to give greater prominence to systems engineering:

“Systems engineering is a discipline that has the widest possible application in designing, managing, controlling and operating complex plants and projects such as process plants, manufacturing systems, bridge building, spacecraft design and robotics. Indeed, increasingly, systems engineering is the solution to the grand challenges that face society – which are large, complex and systemic in nature – and to which engineering can contribute.” ... “Systems engineering should have an overarching and leading role in chemical engineering teaching today to ensure that chemical engineers fulfil their potential in areas such as energy, water, food and health.”

The message of these comments is that the current and future challenges faced by society and industry demand the use of systems approaches to help conceive, design, implement and operate increasingly interconnected engineered solutions, and to support the development of a wide range of new industries. Future engineering graduates must be competent, skillful and innovative as they tackle challenges from a systems perspective.

3. Current status of Process Systems Engineering education

Key to addressing a systems perspective in education is the extent to which PSE is included in the education of chemical, biochemical and process engineers. There is significant variation in the way it is practised across different countries and universities. There is no agreed standard around the core body of knowledge and practice. The presence, breadth and depth of PSE elements depend strongly on the number of faculty members with a background or research focus in process

³ Presentation to The Institution of Chemical Engineers, Special Interest Group in Computer Aided Process Engineering (CAPE), February 3, 2014. See: http://www.icheme.org/media_centre/news/2014/the-cinderella-of-the-chemical-engineering-curriculum.aspx#.W15RS9IzaAM

systems engineering and on their specializations and preferences. World-wide, there have traditionally been two core elements of PSE in chemical engineering undergraduate programs: a design course and project, and a course on process dynamics and control.

In the case of process and plant design, there are different drivers and challenges in its delivery and outcomes in chemical engineering programs. This is because ‘design’ is a key criterion for external, professional accreditation of most degree programs. This is a common criterion across Europe^{4 5}, and also in USA⁶, Australia⁷, New Zealand⁸ and other jurisdictions. Design is recognized as a key graduate attribute and engineering skill by global agreements such as The Washington Accord⁹.

The degree of emphasis and level of capability in design practice varies from one country to another. The specific design-related learning outcomes and the pedagogies or andragogies¹⁰ used vary greatly across universities and countries. For some it is a “capstone” activity, for others it is a theme developed as a staged set of increasingly complex design activities across the whole curriculum.

In the USA, design is generally taught within a final year ‘capstone’ course, which is a major criterion that ABET (Accreditation Board of Education and Technology) uses to provide professional

⁴ See EUR-ACE under the European Network for Accreditation of Engineering Education (ENAAEE),

<http://www.enaee.eu/accredited-engineering-courses-html/accredited-engineering-degree-programmes/>

⁵ See Engineering Council: <https://www.engc.org.uk/education-skills/accreditation-of-higher-education-programmes/information-for-higher-education-providers/>

⁶ ABET (Accreditation Board of Education & Technology): <http://www.abet.org/accreditation/>

⁷ Engineers Australia: <https://www.engineersaustralia.org.au/About-Us/Accreditation>

⁸ Engineering New Zealand: <https://www.engineeringnz.org/resources/accredited-engineering-qualifications/>

⁹ Washington Accord of the International Engineering Alliance: <http://www.ieagrements.org/accords/washington/>

¹⁰ See Section 5.3 for more details on pedagogy and andragogy. The term andragogy comes from the Greek ἀνδρας (men) and αγωγή (education, training) and it is often used to denote adult education.

accreditation to chemical engineering departments in the United States. The design course emphasizes the suitable combination of processing units into an overall system that fulfills the specifications on product properties, emissions, and plant safety in the most economic and long-term sustainable manner. Teamwork is another major goal within the context of each design project.

Education in systems thinking was a core curricular element well before modern PSE tools for the systematic development, validation and optimization of process designs became available. Such tools are now employed also in the design projects, mostly for flowsheet simulation or design tasks for individual elements. Systematic approaches and the use of optimization tools are not standard practice. In the US and other locations, a long-term trend has been to “outsource” the design course to adjunct faculty such as professional engineers, due to the lack of capable academic staff. Best practice seems to rely on course co-ordination from academic staff supplemented by industry experts who provide specific input across the design process.

As for undergraduate process control, the emphasis has been on the study of linear dynamics and linear feedback control. Concepts of open-loop and closed-loop stability, and tuning of PID controllers are also covered. Due to the introduction and utilization of mathematical tools which are not used in other courses, the classical control courses can be somewhat isolated from the rest of the curriculum and therefore may not realize the full potential to contribute to the understanding of dynamics and the enhancing of systems thinking. In the case of optimization, few academics teach it as a required undergraduate course apart from the cases in which a few lectures on optimization form part of either a process design course or a numerical methods course.

At the graduate level, the trend in PSE education is heavily dependent on whether or not there are faculty in the PSE area. If there are none, typically no graduate PSE courses are offered. On

the other hand, if there are, major graduate courses and/or topics covered include computational methods for process simulation, mathematical programming, advanced dynamics and control, process synthesis, planning and scheduling, supply chain optimization, and more recently big data and machine learning.

The current situation provides significant opportunity for change, particularly to enhance PSE components in the core curriculum and to use such components to aid curriculum integration.

4. Core elements of PSE education

In our view, there are a number of *core elements* of PSE education which span several knowledge domains that are coupled to associated competencies, professional abilities and attitudes. These should define the desired learning outcomes for students. The four core elements are:

1. System modeling and simulation
2. Optimization
3. Dynamics and control
4. Process and plant design.

The overarching aspect in these elements is that of systems thinking in order to approach the design and operation of processing facilities and their supply chains from a holistic, integrated point of view. There is a need to apply modeling, optimization, management and control on multiple levels, taking into account the interactions among spatiotemporal scales.

4.1. System modeling and simulation

The description of the phenomena that are encountered in chemical processes by mathematical models is the core of chemical engineering and provides the basis for any systematic exploration

of the design space in plant, process, equipment, infrastructure and product design. It is omnipresent in the basic subjects such as fluid mechanics, heat and mass transfer, reaction engineering, separations and the like. What PSE specifically adds in the area of modeling is a structured, unified approach to the modeling of complex, interconnected systems on multiple scales in space and time.

PSE provides chemical and process engineers the tools to simulate all kinds of processing systems, from individual units to complete plants or sites, and to perform interactive design studies or analyses of various situations for a wide range of purposes. The fundamentals of these tools should be taught early in the undergraduate curriculum so that future engineers have a basic understanding of how the tools work and what problems may be encountered when using them.

A basic education in system modeling and simulation could include the following topics:

- Top-down approaches to modeling large systems
- Steady-state and dynamic conservation principles and constitutive relations
- Structural representation (graphs, networks, connectivity, recycles, hierarchies)
- Description of the properties of materials, with thermodynamics as the core
- Mathematical representations (steady state/dynamic models, discrete/ continuous/ hybrid models)
- System formalism (input-output models vs. causal models, variables, parameters, disturbances, degrees of freedom)
- Uncertainty and information content (accuracy, precision, distributions, parameter estimation, data reconciliation, confidence intervals, sensitivity analysis)
- Numerical solution methods for steady state and dynamic models and their evaluation (convergence, accuracy, stability, multiple solutions)
- Software tools
- Modeling and simulation of combined continuous-discrete behaviors (state transitions, logic controllers).

The above topics could be covered in a single course or distributed amongst various courses. Such courses should ideally build upon the modeling of basic physical entities combined with chemical

and biological kinetics and transport phenomena as developed in other core courses, laboratories or pilot plant activities. The envisaged curriculum should provide an embedding of the knowledge into a general framework that can then be applied to new problems and domains. Modeling should be given a central role across the whole of the degree program – from entry to exit. It should cover the complete field of chemical engineering modeling in an umbrella-like fashion, starting with structuring and abstracting the process into a topology, the use of conservation principles and constitutive relations. The link to the description of the properties of materials is essential for describing behavior of holdups and transfer systems.

Control can be added via measuring state-dependent quantities and manipulating the flows in the transfer systems. This provides a link between the education in physics, chemistry and biology, thermodynamics and transport phenomena. Connecting this to laboratory work or pilot plant activities will reinforce the concepts via experimental learning opportunities. Basic ideas of data quality, parameter estimation and model validation should be introduced. A significant component of time- and length-scale discussion should reflect the fact that assumptions are made explicitly and implicitly during the modeling process. Such learning should evolve around dynamic systems with stationary operation being a special, but important case.

An advanced course in modeling could extend on state-of-the-art technologies and provide the link to areas such as Computational Fluid Dynamics (CFD) and molecular modeling. Approaches to scale interactions and the generation of surrogate models could be covered for those parts whose descriptions are computationally too intensive, making their integration into a larger-scale model infeasible. Criteria for indicating the need for model refinement or model reduction

provide the means to extend or reduce the model complexity and/ or dimensionality. Model reduction should be discussed on the basis of time and length scales using mechanistic-motivated arguments which are to be augmented by mathematical methods such as the methods from linear systems theory and approximate modeling of systems governed by partial differential equations.

In a more application-oriented approach, the subject of interoperability can be introduced providing the background for the generation and use of multi-disciplinary integrated computational environments which will evolve over the next decade. Systematic model generation and representation is connected to the systematic generation of data communication interfaces that make it possible to bridge the barriers between disciplines and address large-scale societal challenges.

An additional possibility (possibly at the Master or PhD level) is to offer an elective course in data analytics, feature detection and extraction and artificial intelligence methods, to further motivate aspiring graduates to stay abreast of the latest developments in big data, machine learning etc., and to be able to critically assess the promises and limitations of such techniques in comparison to the traditional chemical engineering modeling approach.

4.2. Optimization

Optimization techniques are routinely used in plant, process, equipment and product design, process operations and supply chain management. The next generation of engineers must be familiar with the formulation of various engineering challenges as optimization problems along with the most important techniques for their solution, the range of application, the strengths and limitations.

Before considering optimization, there is the need for students to acquire some basic mathematical skills, such as calculus and linear algebra. Modeling concepts for steady-state and dynamic conditions would be assumed as background for a first course on optimization at the undergraduate level.

Rather than solely covering theory and methods, an introduction to optimization in combination with application examples is preferred. Therefore, an optimization project with different milestones to be pursued by groups of students seems to be appropriate. The focus in learning should be on mastering fundamental concepts of optimization and not on detailed algorithms to solve specific classes of problems. Accordingly, emphasis should be placed on recognition and classification of optimization problems, optimality criteria, and problem formulations complemented by a general introduction to major algorithms and their software implementations.

Key topics could include the following:

- Casting real-world problems into mathematical optimization formulations
- Recognising and specifying key elements of optimization problems
- Types of variables: discrete (integer, binary) / continuous
- Types of functions: linear / nonlinear, continuous/ discontinuous, differentiable / non-differentiable, constrained/ unconstrained optimization problems, convexity
- Classes of optimization problems: linear (LP) and quadratic programming (QP), non-linear programming (NLP), mixed-integer linear (MILP) and non-linear (MINLP) or integer programming (IP)
- Optimality conditions
- Overview of major algorithms: Direct search methods, gradient-based methods, simplex algorithm for LP, reduced gradient, successive quadratic programming (SQP), meta-heuristics, rigorous global optimization
- Branch-and-Bound (B&B) for MILP and MINLP
- Optimization modeling software (e.g. GAMS, AMPL, Pyomo, Julia)

Application examples should form a core element in such an optimization course. The following list provides a few examples related to different applications:

- Linear programming (LP) problem for a simple mass flow process based on splits (SIMPLEX)
- Gibbs energy minimization (NLP)
- Utility cost minimization (LP)
- Heat exchanger network synthesis (LP, MILP, MINLP).

It is important that the problems and results are understandable, so that the students can check if the solutions are what they would expect. Visualization in 2D or 3D helps understand the basic principles such as the Karush-Kuhn-Tucker (KKT) conditions for constrained optimization and the integration of Lagrange multipliers. Examples for such projects can be found on the CACHE website¹¹ and MINLP Cyber Infrastructure¹² site. Also, illustrations of optimization models can be found on the CAPD¹³ website at Carnegie Mellon University. It is highly desirable that some rigorous optimization is performed within the design projects.

For advanced optimization, theoretical and algorithmic topics could include:

- Review of basic concepts of optimization (convexity) and the optimality conditions
- Karush-Kuhn-Tucker (KKT) optimality conditions
- Nonlinear Programming (NLP) algorithms (reduced gradient, successive programming, interior point)
- Linear Programming (LP) with Simplex and interior point details
- Modeling of discrete and continuous decisions
- Propositional logic, modeling of disjunctions
- Mixed-Integer Linear Programming (MILP) with Branch-and-Bound details
- Mixed-Integer Nonlinear Programming (MINLP) with details on Branch-and-Bound, Generalized Benders Decomposition, Outer-approximation, Extended cutting plane
- Decomposition methods
- Global optimization
- Optimization under uncertainty.

¹¹ <https://cache.org/super-store/cache-process-design-case-studies#cache-process-design-case-2>

¹² <http://www.minlp.org/>

¹³ <http://newton.cheme.cmu.edu>

There is plenty of material on optimization-related topics and applications in the Virtual Library of PSE¹⁴. Furthermore, interesting exercises can be assigned to the students by asking them to analyze and improve the MINLP models reported at the MINLP site. These cover many applications (Mitsos, Asprion et al. 2018).

Possible further topics for elective courses are:

- Parameter estimation, design of experiments (ideally, in conjunction with some lab or pilot plant work)
- Superstructure optimization
- Multi-objective optimization
- Dynamic optimization with application in model-predictive / economics optimizing control
- Planning and scheduling
- Optimization under uncertainty

4.3. Dynamics and control

The purpose of a first course in dynamics and control is not to educate control engineers or, even less, loop tuners, but to provide an introduction to system dynamics and to create a basic understanding of feedback control, its purpose, trade-offs and limitations.

All chemical and process engineers should have a fundamental understanding of the dynamic behavior of processing systems and of the mathematical and computational tools that can be used to analyze it. This includes the ability to set up first-principles-based dynamic models, a basic knowledge of dynamic simulation and of the possible pitfalls such as dealing with stiff systems, the computation of equilibrium points, the definition of stability, linearization and local linear

¹⁴ <http://cepac.cheme.cmu.edu/pasilectures.htm>

analysis based on eigenvalues. Starting from such fundamental models, the state-space formulation of dynamic systems will result naturally as a small step of abstraction. State estimation and simple state feedback control can then be introduced on this basis.

In process control, first and foremost, the importance of feedback and feedforward concepts for the operation of real processing plants under the influence of all kinds of disturbances must be understood. The basic goals of feedback control (stationary accuracy, stability and suitable dynamic response) should be explained, and the shaping of the dynamic responses by controller tuning must be discussed.

It is a matter of debate whether Laplace transforms and transfer functions should be used or not. The introduction and use of these theoretical concepts and tools enables a clear, mathematically rigorous understanding of system complexity and asymptotic behaviour, which is otherwise difficult to gain. Laplace transforms and frequency responses are useful for a deeper understanding of controller tuning and robustness, and of controller performance limitations; they are also valuable for studying systems that cannot be described by ordinary differential equations. Moreover, the introduction of Laplace transforms provides training in the fundamental step of abstraction and analysis in different spaces. Whether this is worth the required effort (or students should instead gain experience by emphasizing control loop simulations) remains a controversial issue.

A positive contribution of control theory in the overall context of PSE education in process engineering is that it introduces the key concepts of feedback and stability with mathematical rigor. While the discussion of the choice of controllers for simple control loops and their tuning provides the basis for understanding the principles of control, many control problems in real plants are of multivariable nature with significant coupling between the loops. Hence, at least a qualitative

understanding of the phenomena that arise in coupled systems should be provided, possibly accompanied by tools for the selection of control loops. Model-Predictive Control (MPC) as the state-of-the-art advanced control technology in the industry can also be introduced.

It would be desirable to also provide to students an introduction to discrete or logic systems, as in a process plant there are lots of logical functions implemented to prevent undesired or unsafe behaviors, and to implement start-up sequences. Moreover, some knowledge of real-world automation systems is beneficial, to ensure familiarity with e.g. Distributed Control Systems (DCS), Programmable Logic Controllers (PLCs), Manufacturing Execution Systems (MES). Experience with and exposure to the operation of sensors, their limitations and effect on control performance is also recommended: this can form an element of laboratory and/or pilot-plant exercises.

Control is usually not a favorite subject of chemical engineering students because the tools that are used are different from other knowledge areas, and because of its abstract nature. Using simulation tools early on, providing options to learn by doing and dealing with cases of a realistic complexity, may help attract their interest and curiosity. On the other hand, because control uses abstract mathematical notations and methods, a control course provides education in going from the concrete to the abstract and in using mathematical and computational tools for analysis and synthesis and thus to broaden students' thinking and prospective. As noted, in addition to classroom teaching, lab work should underpin the theoretical concepts, giving room for the exploration of dynamic effects rather than only working on a narrowly defined set of tasks.

A key, persistent message of a dynamics and control course must be that nothing works in reality exactly as designed and planned in reality. Therefore sensing and acting during operations are

required to achieve the specified targets of any process in an energy- and resource-efficient manner and to guarantee its safety. Another basic insight is that processes have to be steered to the desired operation from an empty and cold plant. This directly relates to flowsheet design which must be such that all important and/or not self-controlling variables are measured and that sufficient potential for acting on the plant and moving it to the desired state is present. At least for some elements of the plant, procedures for start-up and both planned and safety-related shut-downs should be included in the tasks of design projects.

Electives in the domain of dynamics and control could include:

- Dynamic models (partial differential equations, systems of differential and algebraic equations) and their properties), numerical methods, and dynamic simulation
- Data-driven linear and nonlinear dynamic modeling (system identification)
- Multivariable Control (especially model-predictive and economics optimizing control)
- Logic control (specification and design of logic controllers using formal methods and tools, hybrid dynamics)

4.4. Process and plant design

Proficiency in process and plant design is a key requirement needed to satisfy professional accreditation standards (ABET, UK-SPEC, EUR-ACE, Washington Accord etc.). Its development has traditionally been achieved in a “capstone” course, but many innovative engineering programs have adopted a curriculum where design concepts begin on entry to a program, and are incrementally enhanced and expanded from one year to the next.

For chemical, process engineering and cognate programs (biochemical, biological, environmental, metallurgical and the like) the principal reasons for design education include:

- Engagement with complex, multi-unit designs that meet a wide range of socio-environmental performance specifications subject to constraints

- Integration of past learning in basic sciences and chemical engineering sciences to systems design
- New learning around design philosophies and practice for complex systems
- Generation of alternative and innovative solutions addressing the conceptual design phase
- Application of synthesis and analysis for complex processes
- Decision making under uncertainty and ambiguity
- Optimization of designs focused on areas such as economics, energy and environmental impact
- Further development of research related skills
- Design of specific equipment or operating units
- Applications of inherently safer design principles on process safety.
- Sustainability considerations
- Consideration of risk (environmental, personal, societal, business and reputational)
- Application of safety and risk analyses to minimize failure impacts
- Controllability, operability and maintainability of process
- Management of information during design
- Consideration of economics (from selection of materials, process routes and products, to full profitability assessment)
- Consideration of enterprise aspects (market analysis, financing options, business model)

There is broad consensus, as reflected in professional accreditation guidelines, that design projects contribute significantly to developing important professional attitudes, practices and dispositions that should include:

- Ethical conduct
- Making decisions under uncertainty and resolving ambiguities
- Developing a creative, innovative and proactive attitude
- Working in teams, and managing team dynamics, accountabilities and leadership
- Handling project constraints regarding time, information and other resources
- Effective communication amongst team members as well as external communication to clients via spoken, written, visual and graphical means. Multi-lingual skills are often required as well.

To achieve such learning outcomes within a single course is not realistic. Certainly, many areas can be addressed and skills can be developed – but only to an introductory level. This raises the

challenge for curriculum designers to create numerous opportunities during a 4- or 5-year program to embed systems thinking and design-oriented practice throughout the whole curriculum, and slowly build skills and competence across numerous years rather than rely solely on a single course to achieve such outcomes required for entry into professional practice.

Another important area is risk and process safety, an inherently socio-technical system necessity. This is an essential area of graduate expertise but is poorly addressed in many curricula due to similar challenges that process design education possesses.

There are however numerous examples where innovative, comprehensive curriculum designs have been adopted with significant success, and with global recognition.¹⁵

5. Curriculum Design

Curriculum design and implementation is a multiscale problem. It consists of considerations across the whole curriculum that represents a degree program, as well as learning years, individual learning units and the learning pathways in those units. There are also important timescales at work: major curriculum changes which can be of 10-20 year cycles; program year changes of shorter duration and unit learning changes that can be of 1 to 5 years. The design of learning around systems concepts and applications cannot be divorced from other areas of engineering learning that are also taking place. Key concepts to consider are:

- Curriculum goals: what are we trying to achieve across a program?
- Curriculum structures: what are the knowledge areas and how are they arranged?
- Curriculum pedagogy and andragogy: how do students engage in learning?

¹⁵ See the studies by Ruth Graham mentioned in section 5.2

5.1. Curriculum goals

Curriculum is the development of interconnected learning pathways that address learning outcomes¹⁶.

The challenge in whole-of-curriculum design is to develop learning pathways where the knowledge areas, application skills and professional competencies of the graduate are progressively acquired, exercised and matured. Specific curriculum choices are guided by:

- The emphases and strengths of individual institutions
- The differentiation in graduate profiles that are adopted for diversity reasons between institutions
- The need to satisfy professional accreditation guidelines that provide assurance around the quality of graduate engineers¹⁷

This is both a design problem for the pathways – typically a top-down design approach based on outcomes, and adoption of ‘best practice’ pedagogy and/or andragogy that help drive learning.

Engineering organizations such as the International Engineering Alliance (IEA)¹⁸ or the European Network for Accreditation of Engineering Education (ENAAE)¹⁹ permit flexible interpretations on desired outcomes, thus permitting innovative curriculum designs. PSE can act as a corner stone for the whole curriculum (Cameron, Douglas et al. 1994).

¹⁶ The word ‘curriculum’ derives from the Latin ‘*currere*’ meaning to run. It was often used in reference to Roman racetracks and chariots. Hence the idea that curriculum represents the course or pathway of learning.

¹⁷ The issue of global, national and regional (state) professional accreditation has been briefly discussed in the section on “Current status in Process Systems Engineering education”.

¹⁸ Refer to: <http://www.ieagrements.org/>

¹⁹ Refer to: <http://www.enaee.eu/>

5.2. Curriculum structures

The presence of learning modules/courses in a curriculum, their sequence and interconnections provides the curriculum structure. For engineering curricula there are at least 4 principal knowledge areas:

1. Basic sciences (mathematics, physics, chemistry, biology, ...)
2. Engineering sciences and chemical engineering sciences (thermodynamics, heat and mass transfer, reaction, transport phenomena, etc.)
3. Systems related learning (process analysis, process design, design and control system synthesis, dynamics and modelling, process control, safety, risk and environment, statistics and economics, etc.)
4. Electives for breadth and depth (economics, business processes, ICT, food technology, biomedical, biotechnology, nano-technology, etc.)

Big picture level

The systems-related areas in curricula have their own sets of learning outcomes, but also have an integrative role for other parts of the curriculum. Figure 2 shows a general curriculum design for a 5-year program. In Europe this may be split between undergraduate and Master programs as 3+2 years, or 3 ½ + 1 ½ years (most of the European Union) or 4+1 (e.g. UK) . It possesses a set of learning pathways that are integrated both vertically and horizontally, with emphasis on project driven systems-related learning (Crosthwaite, Cameron et al. 2006). The underlying design principles include:

- Development of the basic sciences as well as the engineering sciences
- Provision of pathways using systems-related courses that progressively deal with:
 - A progression in design thinking
 - Progression in systems conceptualizations and systems thinking
 - Growing complexity and ambiguity of contexts
 - Opportunities to horizontally integrate basic and engineering sciences into systems related problems
 - Progressive development and exercise of critical thinking skills
 - Professional skills development

- Opportunities to broaden and deepen individual education via elective pathways that might pursue such areas as:
 - *Broadening*: business and innovation skills, human factors in engineered systems, nano-technology etc., or
 - *Deepening*: advanced modeling, control, optimization etc.

The key to excellent curriculum design is to effectively address:

- Clearly defined outcomes for learning units, that address the knowledge, skills and professional attitude elements
- Teaching and learning activities that effectively engage students, and
- Aligned assessment strategies against desired outcomes. This is related to the well-established educational principle of “constructive alignment”, since in any system you need to have appropriate assessment to verify your outcomes of interest. (Biggs 2003).

PSE areas are important in their own right and they have the capacity to help integrate other areas of the curriculum that can sometimes be “orphaned”. Curricula that do not consistently have integrative activities often lead to a ‘siloe’d’ view , due to the inability of many students to see the significance and importance of their activities in individual courses.

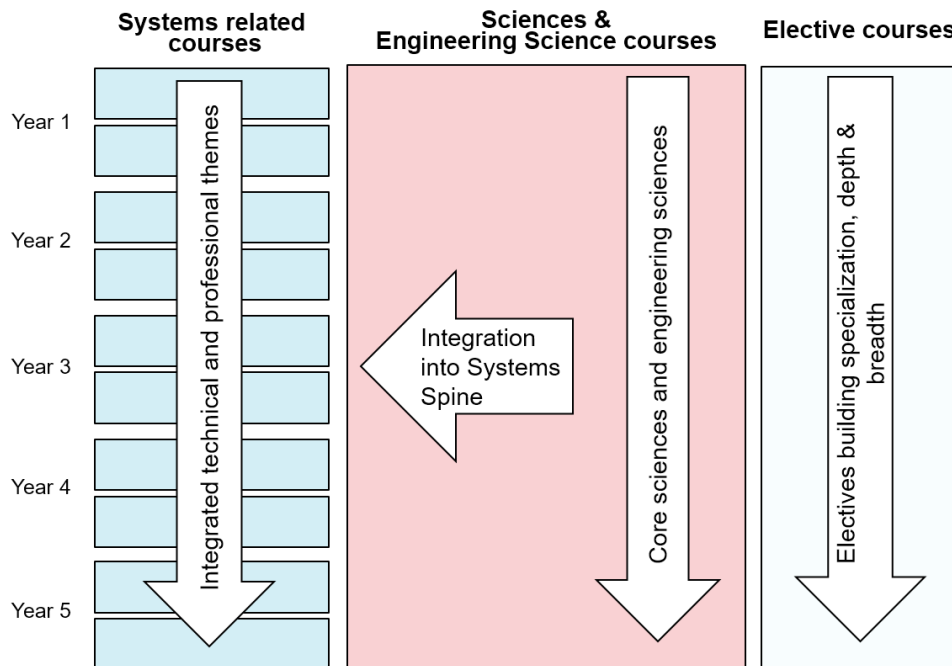


Figure 2: An integrated curriculum design with systems-related spine

Most institutions adopt the “course” as the defined learning unit for reasons of efficiency with large student numbers, timetabling and academic ownership of knowledge areas. This immediately sets constraints on curriculum innovation. However, within those constraints, learning designs can be devised to better engage students with more integrated learning through industrial and research projects. Recent global studies conducted by Dr Ruth Graham give a range of successful innovations that have driven major curriculum change (Graham 2012, Graham 2018). These review studies provide useful insights for designing innovative curricula. Where those constraints are relaxed more creative approaches are definitely possible.

Project based integration approaches

Figure 3 shows a project centered curriculum design built from a major program review . This has both a 4-year (Bachelor) exit point as well as a 5-year (Master) exit point²⁰. The design and delivery focuses on progressively building systems perspectives and thinking through 5 years, driven by PSE-related courses. Integration is vertical and horizontal. The learning in PSE-related courses is driven through a range of industry focused projects.

For example, in later years, risk and process safety student teams take real industry scenarios with all the control and engineering data, process design, operational documentation, with the task of unravelling what happened, why it occurred and how both technical systems and human interactions could be redesigned and implemented. Site visits and virtual reality tools assist in driving a range of systems thinking.

²⁰ This is the current Chemical Engineering program at The University of Queensland. Details of the complete program with all course outlines is available at: https://my.uq.edu.au/programs-courses/plan.html?acad_plan=CHE-MIX2350&year=2019

This particular curriculum also permits the development of specialisations through elective streams, such as biological, environmental, metallurgical or materials areas.

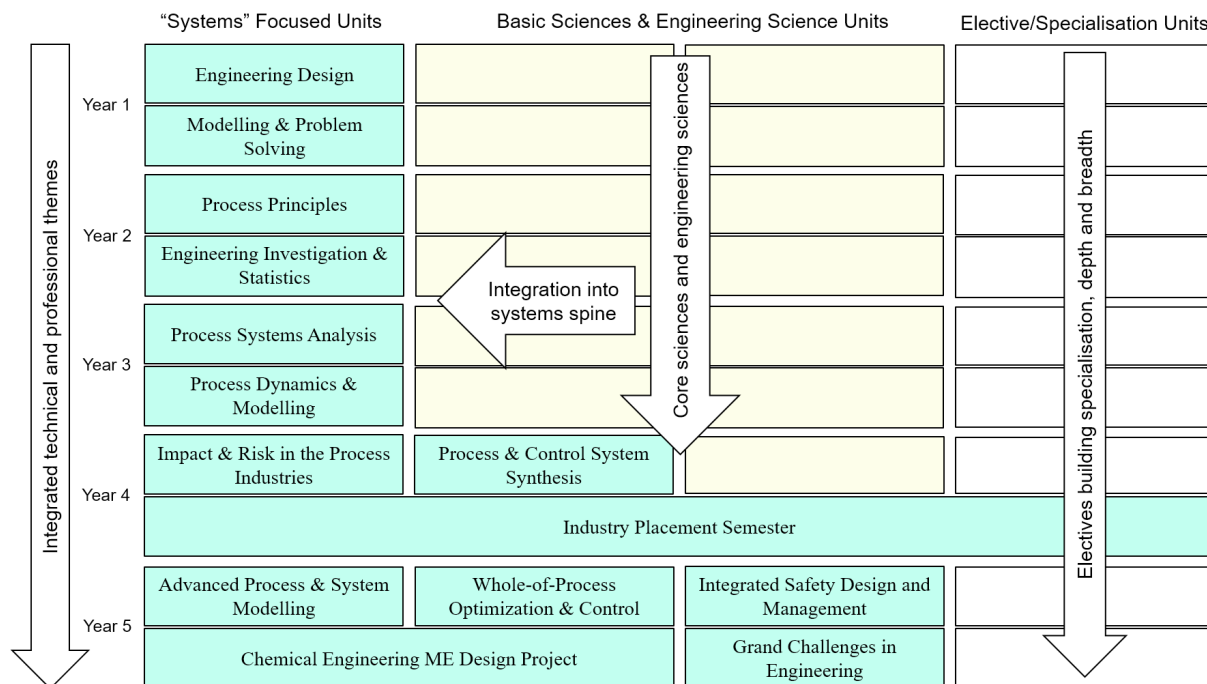


Figure 3: Curriculum design with focus on process systems concepts across 4 or 5 year program

Other institutions have different, but complementary approaches to curriculum design. For example, instead of standalone, semester long courses for specific PSE-related areas such as modelling, control or optimization, these principles and practices can be acquired within design or project activities that integrate such knowledge areas²¹. These integrated approaches can be very beneficial to students' understanding of complex process systems. These approaches require very good learning management and oversight, but have the added bonus of engaging students with industry challenges and professional practitioners.

²¹ See MIT Chemical Engineering subjects such as Integrated Chemical Engineering 10.490, Integrated Chemical Engineering Topics 10.492, 493, 494, or Engineering Systems Design 2.013. <http://catalog.mit.edu/degree-charts/chemical-engineering-course-10/>

Many institutions use well-defined to complex projects, in building and contextualizing knowledge and application within ambiguous and uncertain situations.²²

Other institutions have adopted the CDIO (conceive, design, implement and operate) approach to engineering education as an alternative curriculum design approach. It emphasizes engineering practice as well as theory to address real-world situations.²³

In some circumstances, many online learning environments can complement traditional class learning. In specific areas of software skills, e-Learning sites can provide principles, practice and assessment of students' learning.²⁴

Problem-Based Learning (PBL)

Problem-Based Learning (PBL) when applied across curricula can provide a learning framework that is strongly student-centered learning. Students normally deal with challenging socio-technical problems that have numerous dimensions of consideration. This provides the vehicle for individual learning and the goal is not necessarily to get a specific solution but to develop knowledge acquisition, critical review and reasoning skills. Some engineering programs have adopted such approaches.²⁵ It shares many characteristics of the project driven curricula, and the effects of the approach in terms of student outcomes are very well documented.

Engaging students across the whole cognitive and affective learning spectrum

²² See University College London, Integrated Engineering Programme (IEP): <http://www.engineering.ucl.ac.uk/integrated-engineering/programme-structure/>, or see Imperial College London, Chemical Engineering program with multiple design projects each year: <https://www.imperial.ac.uk/study/ug/courses/chemical-engineering-department/chemical-engineering/>

²³ See the CDIO site at: <http://www.cdio.org/>

²⁴ This can relate to process flowsheeting, control theory and practice etc. In the area of data science the DataCamp environment is readily available to institutions and their students, see: <https://www.datacamp.com/>

²⁵ See Chemical Engineering & Biotechnology program at Aalborg University, Denmark: <https://www.en.aau.dk/education/problem-based-learning/project-work/>

In developing learning designs it is crucial that students are constantly challenged to move across the whole of the Bloom's Taxonomy cognitive and affective levels (Anderson and Krathwohl 2001). This ensures students are being challenged in: Knowing, Understanding, Applying, Analyzing, Evaluating, Synthesizing or Creating. These are not linear and progressive. The taxonomy can be used to engage students via a synthesizing activity, then look at analyzing and evaluating the generated options with knowledge or research needed to understand deeper issues. Such activities are very well suited to PSE-related areas.

Affective considerations should also be part of the learning design, creating opportunities for students to be aware of, and develop professional attitudes as future professional engineers.

Underlying pedagogy and andragogy principles in what has been discussed are to be found in the Appendix.

6. Present and future challenges – what educational responses do we make?

There are two kinds of challenges that all who are involved in teaching chemical engineering and related disciplines have to address: new content and new technology for education. The progress of science and technology is faster than ever and there is a continuous pressure to integrate new approaches, methods, tools, and technologies into the curricula. The most prominent example at the moment are the methods and tools from Information and Communication Technology (ICT), in particular (big) data analytics, data-based models and decision support, machine learning. Access to data, also in real time, will be less and less of a problem, due to the progress in communication technology and formal models and descriptions of data that enable interoperability of different IT-based systems. While the accessibility of data will improve greatly, the quality of data

does however not increase at the same pace, due to the persistent problems of measuring crucial process variables accurately and fast and at a reasonable cost. This provides one of many challenges for the application of tools from data analytics that are rooted in the analysis of business data to processing systems.

Techniques for data processing, including filtering and state estimation, statistical analysis, data-based modeling are already part of the PSE “tool-kit” and education, but usually not very prominent in curricula. Increasing the breadth and depth of the education in this area will be required and will also further improve the already excellent position of chemical engineers on the job market. Their position is excellent because they are equipped with the fundamental insights into the physics and chemistry of processing systems and with systems thinking which is usually lacking with pure data scientists. It will be a matter of continuous scientific debate and experimentation in research and development projects where and to which extent purely data-based modeling techniques can be successful and how they should be integrated with the fundamental insights and models that are traditionally used in process systems engineering. The results of this debate and of the many ongoing R&D projects in this area will then lead to reforms of the chemical engineering curricula. . In any case, a growing importance of statistics is envisaged.

Models and simulation will become even more important in the future, providing the basis for the integrated analysis and for decision support for the design and operation of processing systems over the full life cycle, from strategic planning, through research, conceptual design, design, construction, operations, decommissioning, restoration. The current buzzword of “digital twins” highlights this trend. As more and more complex systems and dependencies can be modeled and simulated, data visualization becomes crucial to bring such simulations to productive use.

The second challenge concerns the use of modern technology for education. Students today are used to different tools and technologies for communication and exchange of information. These technologies can provide means to better engage learners in the educational processes. Social media, access to new devices and tools, and the easy access to information are changing the learning landscape. How best to exploit them needs serious consideration. After all, the simple collection of facts, pseudo-facts, claims, statements and images does not create insight and solutions to challenging problems. It is key to create educational environments such that graduates develop analytical and deep critical thinking skills overlaid on deep understanding of complex systems.

State-of-the-art technology may provide much more efficient means to support the fundamental understanding of both the basic laws of physics and chemistry that are important in processing systems and the interaction of their different elements and aspects that leads to complex behavior. How, when and where can virtual reality (VR), augmented reality (AR) and/or mixed reality (MR) technologies be integrated into PSE educational activities to derive benefit in learning about complex phenomena and system behaviors? How can inductive learning, in contrast to deductive derivations from basic principles, be supported with modern technology?

These issues represent just some of the interesting and important 21st century developments and questions that will need consideration. As in all areas of education, we expect to see innovative initiatives and an evidence-based uptake of the successful ones, especially in a fast-moving innovative discipline like PSE.

7. Concluding Remarks

The whole is more than the sum of its parts – this is a fundamental insight from which PSE derives its mission. This is also true for engineering education. The mindset of an engineering graduate who has finished a specific program at some institution is not the sum of the learning outcomes of all the modules he or she has studied. Some of the material will be partly forgotten, depending in particular on whether it was used in project work or not. On the other hand, a specific persistent set of concepts, tools and skills to approach, analyze, categorize and formalize problems, to synthesize solutions and to evaluate them will emerge. An important characteristic will be the ability to engage with other disciplines and professionals in a co-operative manner, providing the intellectual and methodological “glue” in interdisciplinary projects. This is the result not only of what is learned but also of how it is done, and of the breadth of the curriculum and the depth of its elements. These abilities will accompany a student throughout his or her professional life, across industry sectors, roles and technologies.

PSE methods help cast complex phenomena and the requirements that the engineers meet, coming from their companies, the environment and society, into a logical and mathematical framework. This way, the problems are amenable to the application of analytical and computer-based tools that provide insight into constraints, trade-offs, and attainable results on solid grounds, rather than based on experience or first order approximations. If the graduates of chemical and biochemical engineering programs have – inter alia – acquired the mindset to approach real problems in this “PSE way”, they will serve their future employers and society well.

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Appendix: Curriculum and course design concepts

In considering the educational importance of PSE, key graduate outcomes involve three principal areas, as outlined by Barnett & Coate (2005), as seen in Figure A1:

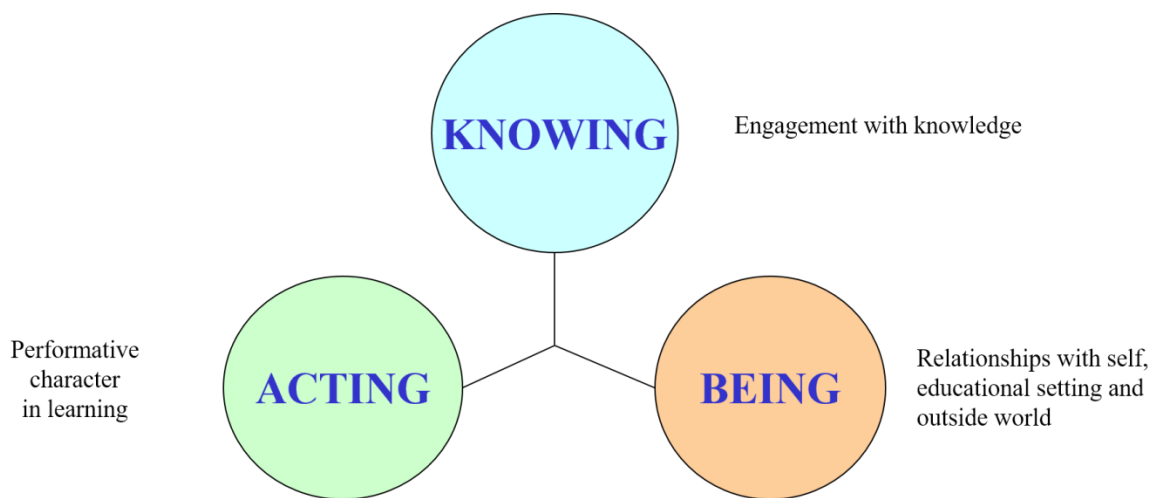


Figure A1: The Knowing-Acting-Being (K-A-B) schema for learning and design of curricula

Professional accreditation standards or requirements typically express their outcomes under similar categories.

Curriculum pedagogy and andragogy

Students can be engaged with learning processes through different pedagogy and andragogy. Pedagogy relates primarily to a teacher-driven model, whilst andragogy incorporates a move towards self-directed learning. The latter model is particularly important as students move towards professional practice.

Process Systems Engineering, as a vital part of a chemical engineering program, needs to consider the engagement of theory and practice in smarter, effective ways. There are a number of considerations as seen in Figure A2. They include:

- **PEOPLE:** who are the people that are interacting with students and what do these people contribute to the learning environment? This can involve academics, tutors, mentors, industry representatives, people from other disciplines, technicians or recent graduates.
- **PLACES:** what are the spaces and places where learning occurs? This can range from lecture facilities to laboratories, pilot plant facilities, design studios, industrial sites or company offices. It can be in virtual spaces too. Each of these spaces/places has its own affordances, where some activities can or cannot occur. The clever use of spaces in the curriculum can enhance learning. This is particularly important in systems-related learning.
- **PROCESSES:** These are the methodologies deployed to give structure to the week-to-week or semester-to-semester learning. Amongst such approaches are problem based learning (PBL), project based learning (PjBL), Conceive-Design-Implement-Operate (CDIO) approaches, or potentially Work Integrated Learning (WIL), industry internships and Peer Instruction. This aspect can include Computer Aided Learning (CAL), self-paced learning, workshops, intensive sessions and lectures/tutorials/recitations. The choice of when and where individual and team-based learning is adopted is important in developing graduate capabilities.
- **PROBLEMS and PROJECTS:** the choice of problems and more involved project approaches help drive learning through embedding knowledge, exercising skills and developing professional competencies. Strategically chosen problems and projects can help address threshold learning concepts, addressing well-posed to ill-defined and complex situations, exercising decision making in many ways. Care needs to be given to the strategic use of problems and projects as learning outcomes are addressed.
- **PERFORMANCE:** the curriculum design should consider ways to stimulate and enhance motivation, ways to measure the achievement of the desired outcomes (both qualitative and quantitative), in particular for the professional skills elements such as teamwork, and assessment procedures, including the use of self-assessment and peer-review.

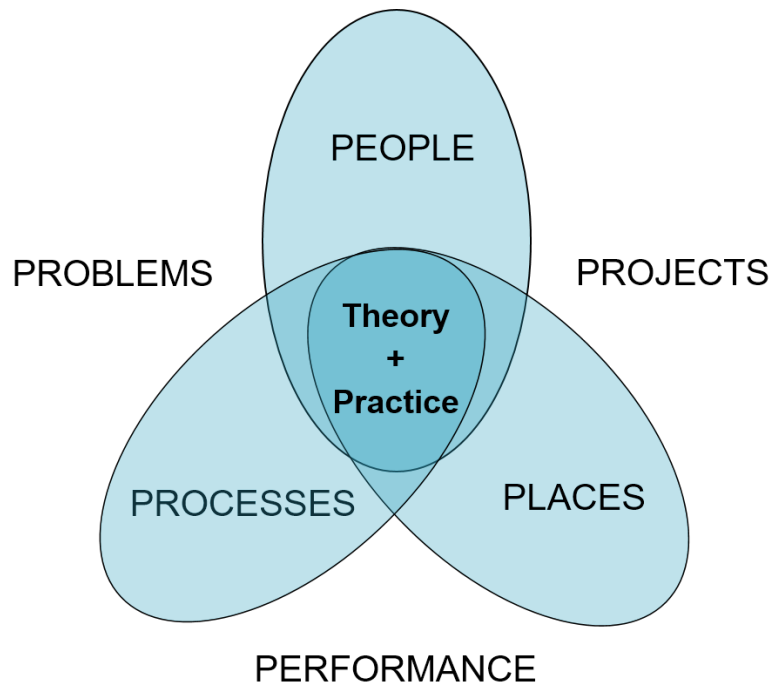


Figure A2: Dimensions to consider in creating learning environments

Using these 6 dimensions in creative ways can lead to engaged learners. Learning innovation will come from evidence based research, experimentation and the willingness to be creative. A further challenge in curriculum design is that it involves many faculty members with competing claims for various core or specialty areas.

Even so, the ideas of developing strong system thinking and the requisite engineering and professional skills for graduates can be a point of faculty collaboration. Indeed, in some universities supervising and mentoring student groups across design-related courses has been seen as an excellent training development step in collaboration and system thinking for new academics.